BELL'S INEQUALITY: MORE TESTS ARE NEEDED

In the last two decades there have been numerous tests of unusual correlations predicted by quantum mechanics between outcomes of particular experiments in space-like separated regions. The peculiarity of these correlations is that they are stronger than any correlations explainable by a local theory. The quantum correlations, as was proven by Bell [1], break certain inequalities which have to be fulfilled if the results of every experiment are determined by some local hidden variable (LHV) theory.

We have been witnessed an outstanding progress in the tests of Bell's inequalities, but a decisive experiment which would rule out any LHV theory has not been performed yet. The deficiencies of the experiments are described by *locality* and *detector efficiency* loopholes. According to recent reports in Nature by Aspect [2] and Grangier [3] the two loopholes were closed.

I want to express an opinion, that the really important task in this field has not been tackled yet and that the leading experiments claiming to close the loopholes, Weihs et al. [4] and Rowe et al. [5], although clearly making a very significant progress, have conceptual drawbacks. These drawbacks have to be removed before claims like "the last loophole closes" can be made.

Today there is a firm consensus that there is no real question what will be the outcome of this type of experiments: the predictions of quantum theory or results conforming with the Bell inequalities. Predictions of quantum mechanics were verified in so many experiments and with such unprecedented precision that, in spite of the very peculiar and nonintuitive features that Bell-inequality experiments demonstrate, only a minute minority of physicists believe that quantum mechanics might fail in this type of experiments. However, the fact that we are pretty sure about the final result of these experiments does not mean that we should not perform them. One goal of such experiments is to change our intuition which developed from observing classical phenomena. But more importantly, these experiments should lead to the stage in which we will be able to *use* these unusual correlations.

Conceptually, the most simple, surprising, and convincing out of the Bell-type experiments is the Mermin's version of the Greenberger-Horn-Zeilinger (GHZ) setup [6]. I find that it can be best explained as a game [7]. The team of three players is allowed to make any preparations before the players are taken to three remote locations. Then, at a certain time, each player is asked one of two possible questions: "What is X?" or "What is Y?" to which they must quickly give one of the answers: "1" or "-1". According to the rules of the game, either all players are asked the X question, or only one player is asked the X question and the other two are asked the Y question. The team wins if the product of their three answers is -1 in the case of three X questions and is 1 in the case of one X and two Y questions. It is a simple exercise to prove that if the answer of each player is determined by some LHV theory, then the best strategy of the team will lead to 75% probability to win. However, a quantum team equipped with ideal devices can win with certainty. So, in my opinion, the most convincing test of the Bell inequality is actually constructing such devices an seeing that, indeed, the team wins the game with probability significantly larger than 75%.

Such an experiment, if successful, will definitely close the detection efficiency loophole. If it is also arranged that the party asking the questions chooses them "randomly" (more about randomness below), then it will also close the locality loophole. Note, that an experiment which simultaneously closes both the detection efficiency and the locality loophole will not necessarily be suitable for winning games of the type I described here. The essential property of the experiment which allows winning games is that when one player observes the result of his measurement, he has to be sure that other players observe corresponding results too. We might imagine an experiment with 100% efficient detectors and ultrafast switches, but with the source that do not always send the GHZ triplets (like in the current GHZ experiment [8]); such devices cannot help in winning the game.

The technology for "winning games" experiments is not quite here yet, so we should still work on "closing the loopholes" experiments. The locality loophole means that the decision of the choice of which local measurement to perform is made long enough before the time of measurements in the other sites such that the information about this choice can be known there. Then, there is no difficulty in constructing a LHV theory which reproduces the quantum correlations. In the experiment which claimed to close the locality loophole, the choices of the local measurements were determined shortly before the measurement by fast quantum experiments at each site. The outcomes of these experiments are "genuinely random" according to the standard quantum theory. However, if we want to rule out LHV theories, we should consider the situation in the framework of such theories. The outcomes of the quantum measurements which determine the choice of the local measurements are also governed by some LHVs in each site. There is enough time for information about these LHVs to reach other sites before the measurements there took place and, therefore, a consistent LHV theory which reproduces the results of Weihs et al. experiment can be constructed. The locality loophole is not closed. The experiment, nevertheless, is a significant step forward because its results can be explained only by a higher level LHV theory in which hidden variable specifying the behavior of one system are influenced by hidden variables of other systems.

A frequently discussed experiment in which the distance between the sites is so large that a person at each

site will have enough time to exercise his “free will” to choose between the measurements will be very convincing, but conceptually, not much better: we cannot rule out the existence of LHVs which are responsible for our seemingly “free” decisions. A better experiment for closing the locality loophole (which does not seem to be impossible with today’s technology) is to arrange that the choice of local measurements will be determined by photons arriving from distant galaxies from opposite directions. Then, the only explanation will be a “conspiracy” LHV theory on the intergalactic scale.

Finally, I will discuss the latest experiment by Rowe et al. [5] who claimed to close the detection efficiency loophole. In this experiment the quantum correlations were observed between results of measurements performed on two ions few micrometers apart. The detection efficiency was very high. It was admitted that the locality loophole was not closed in this experiment. But the situation about locality was worse than that. Again, the locality loophole means that in principle, the information about the choice of local measurement can reach the other sites before the time of measurements there. However, in the Rowe et al. experiment not only the choice, but also the *result* of the local measurement could reach the other site before the measurement there was completed. The reading of the results was based on observing numerous photons emitted by the ions. This process takes time which is a few orders magnitude larger than the time it takes for the light to go from one ion to the other. Thus, we can construct a very simple hidden variable theory which arranges quantum correlations by “communicating” between the ions during the process of measurement.

The purpose of closing the detection efficiency loophole was to rule out set of LHV theories in which the particle carries the instructions of the type: if the measuring device has particular parameters, choose “up”, for some other parameters choose “down” and yet for some other parameter choose “not to be detected”. Such hidden variables cannot explain the correlations of Rowe et al. experiment and this is an important achievement. However, the task of performing an experiment closing the detection efficiency loophole without opening new loopholes is still open.

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